Wi-HTest: Compliance Test Tool for Real-Time WirelessHART^{TM} Mesh Network Devices

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***Abstract*— WirelessHART^{TM} was released in September 2007 and became IEC standard in April 2010 (IEC 62591). It is the first open wireless communication standard specifically designed for real-time process control applications. It is designed to the same standard as its wired counterpart for reliability and interoperability. To ensure the compliance with the HART^{TM} Communication Protocol and the adherence to its strict timing requirements, all WirelessHART devices must be thoroughly tested and registered with the HART Communication Foundation (HCF). In this paper, we present Wi-HTest, the test suite developed to exercise WirelessHART devices, thus facilitating compliance assessment. We discuss the detailed architecture of Wi-HTest and highlight several critical features like packet handling with accurate timing control, fault data injection, and the virtual network approach for scalable test setup. We also describe a sniffer called Wi-Analys for capturing WirelessHART packets along with their timing information and a post process suite for analyzing the packets. These three tools together provide the complete compliance verification environment for WirelessHART. Based on the test specification developed by HCF, we presented several representative test cases for examining WirelessHART devices' behaviors in different layers. These test cases in turn show that Wi-HTest is a novel and efficient test suite for verifying the compliance of WirelessHART devices.**

I. Introduction

Wireless technology has been regarded as a paradigm shifter in the process industry and has received extensive studies recently [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. Compared to traditional wired process control systems, their wireless counterparts have obvious advantages in easier installation, more flexible configuration and lower maintenance cost. However, different from office or manufacturing automation applications, industrial control systems have much stricter timing requirements and higher security concerns. To address these problems, WirelessHART [12] was officially released in September 2007 as the first open wireless communication standard specifically designed for real-time process control applications. In 2010 it became an IEC (International Electrotechnical Commission) standard, the IEC 62591. WirelessHART is a secure and TDMA-based wireless mesh networking technology operating in the 2.4 GHz ISM radio band. It is designed with strict timing requirements and to be highly reliable and interoperable while being easy to install and operate. WirelessHART was engineered to strike a careful balance between cost, simplicity, battery-life and guaranteed real-time wireless communication.

To assure the standard compliance of HART products (including WirelessHART devices), which is key to vendors' success in the market and help them avoid expensive product recalls and technical support costs, since 1995 the HART Communication Foundation (HCF) [13] has operated a rigorous quality assurance program and all HART devices must be thoroughly tested and registered with the HCF. As part of this program, HCF develops detailed test specifications and test tools for HART standards. Along with the release of WirelessHART standard, HCF has developed Wi-HTest, an extension of the original HTest tool to support WirelessHART quality assurance especially focusing on the timing compliance test.[1] HCF has also developed a specific sniffer called Wi-Analys for real-time monitoring of the WirelessHART network and is working on a post process suite for analyzing the packets captured by Wi-Analys and generating the final compliance report. All these three tools together provide a complete compliance verification environment for WirelessHART devices.

As a test suite specifically designed for wireless real-time communication protocol, Wi-HTest has two inherent functionalities. First, it is able to construct the test packets in real-time manner and send them to the DUT (Device Under Test) through 802.15.4 radio with accurate timing; Second, with the help of Wi-Analys, Wi-HTest can capture the response packets from the DUT along with its timing information. These two functionalities enable Wi-HTest to not only check the correctness of the response data but also verify its timing information.

Wi-HTest aims at automating the execution of test cases defined in the WirelessHART test specification. More specif-

[0]An earlier version of this paper appeared in [1].

[1]The product name of Wi-HTest is HCF_KIT-193. it could be purchased from HCF.

ically, Wi-HTest provides the stimulus (good and bad) necessary to exercise operations of the DUT. The test cases for verifying the compliance of WirelessHART devices can be roughly classified into three different test scenarios, the device join process, MAC layer data communication and network layer data communication. In the join process, Wi-HTest coordinates with the DUT through a sequence of message exchanges and verifies whether the DUT can join the WirelessHART network successfully; In the MAC layer communication tests, Wi-HTest transmits either correct data packets or manipulate the packets by injecting fault data. By evaluating DUT's corresponding response including the precise timing information, the DUT's MAC layer compliance can be assessed. Wi-HTest conducts the network layer communication tests by introducing the concept of virtual network and virtual devices. It simulates a WirelessHART network by adding necessary virtual devices and configuring the communication schedules between the DUT and virtual devices or among virtual devices. End-to-end communications are executed by Wi-HTest to evaluate the DUT's network layer compliance by comparing its practical behaviors with the standard ones according to the WirelessHART specification.

In this paper, we discuss the detailed design of Wi-HTest and describe the other two important tools: the Wi-Analys and the post process suite. Based on these three tools, we present several representative test cases to demonstrate the efficiency of our test suite. To the best of our knowledge, this is the first reported effort to build a commercial-grade test suite for WirelessHART standard. Our contributions in this paper are fourfold:

- **Introduction of WirelessHART test specification and test script.** We describe the WirelessHART test specification and present the general format of the test scripts.
- **Description of the architecture of Wi-HTest.** We present the Wi-HTest architecture and highlight the design of several critical features in Wi-HTest. For example, the generation of test packets with accurate timing control, the packet manipulation and the virtual network approach. We also share our first-hand experience in designing and implementing these critical features.
- **Description of Wi-Analys and the post process suite.** We describe the real-time capturing and analyzing features in Wi-Analys and the post process suite.
- **Demonstration of representative test cases.** These test cases demonstrate how Wi-HTest, Wi-Analys and the post process suite work together to assess the compliance of the DUT in different communication layers.

The remainder of this paper is organized as follows. In Section II, we introduce the WirelessHART standard and some existing test suites designed for public wireless standards in office and manufacturing automation. Section III presents the WirelessHART test specification and the structure of the test script. We describe the detailed design of Wi-HTest in Section IV. Section V discusses the functionalities of Wi-Analys and the post process suite. Section VI presents several representative test cases and discusses the advantages and limitations of the virtual network approach. Section VII shares the broad lessons we learnt from the design and implementation of Wi-HTest. We conclude the paper in Section VIII.

II. Background and Related Works

To help vendors assure product interoperability and shorten the time to market, many test suites are available in the market for various wireless standards, such as Bluetooth [14], ZigBee [15], and Wi-Fi [16]. In this section, we first give a brief introduction of the WirelessHART standard and then discuss several existing test suites for well-known wireless standards. We also describe HTest, the test suite designed for wired HART communication protocols. Wi-HTest is an extension of HTest to support WirelessHART quality assurance.

A. WirelessHART Architecture

Traditional wireless standards for office and manufacturing automation cannot meet the stringent timing and security requirements of industrial control. WirelessHART standard is specifically targeted to solve these problems and provide a complete solution for real-time process control applications. Figure 1 illustrates the architecture of the HART protocol according to the OSI 7-layer communication model. As a part of the HART protocol, the architecture of WirelessHART protocol is shown on the right side of Fig. 1. At the very bottom of the protocol, WirelessHART adopts IEEE 802.15.4-2006 [17] as the physical layer. On top of that, WirelessHART defines its own time-synchronized data link layer. Some notable features of WirelessHART data link layer include strict $10ms$ time slot, network wide time synchronization, channel hopping, channel blacklisting, and industry-standard AES-128 ciphers and keys. The network layer supports self-organizing and self-healing mesh networking techniques using source routing and graph routing. In this way, messages can be routed around interferences and obstacles, which greatly improves the network performance in noisy and harsh environments. WirelessHART also distinguishes itself from other public standards by maintaining a central Network Manager. The Network Manager is responsible for maintaining up-to-date routes and communication schedules for the network, thus guaranteeing the real-time network communications.

A typical topology of a WirelessHART mesh network is presented in Fig. 2. All WirelessHART devices support the basic mesh node functionalities, including routing capability. The basic device types of a WirelessHART network are listed as follows.

- **Network Manager** is responsible for configuring the network, scheduling and managing communication among WirelessHART devices. It is implemented as a software that resides in the Gateway or the Host.
- **Gateway** connects Host applications with the field devices. There is one Gateway per one WirelessHART network.

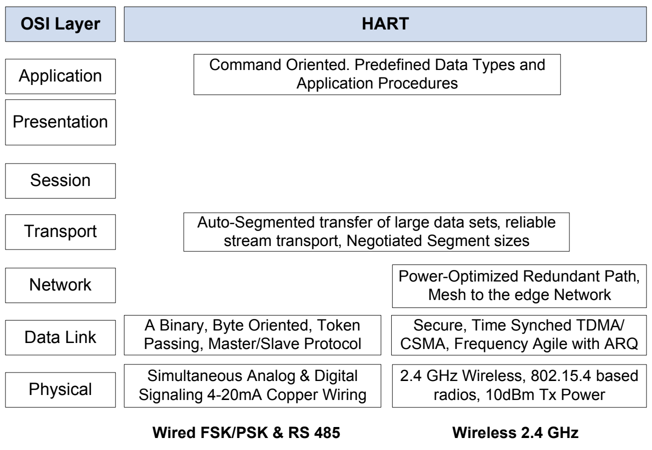

OSI Layer
HART
Application
Command Oriented. Predefined Data Types and Application Procedures
Presentation
Session
Transport
Auto-Segmented transfer of large data sets, reliable stream transport, Negotiated Segment sizes
Network
Power-Optimized Redundant Path, Mesh to the edge Network
Data Link
A Binary, Byte Oriented, Token Passing, Master/Slave Protocol
Secure, Time Synched TDMA/ CSMA, Frequency Agile with ARQ
Physical
Simultaneous Analog & Digital Signaling 4-20mA Copper Wiring
2.4 GHz Wireless, 802.15.4 based radios, 10dBm Tx Power
Wired FSK/PSK & RS 485
Wireless 2.4 GHz

Fig. 1. The architecture of HART communication protocol

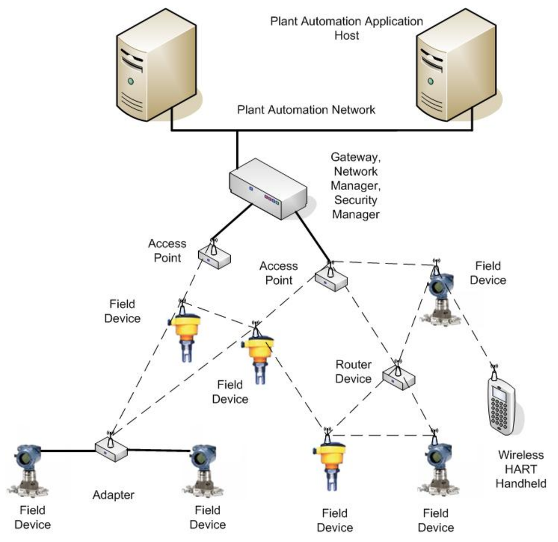


Fig. 2. A typical topology of a WirelessHART mesh network

- **Access Point** is attached to the Gateway and provides redundant paths between the wireless network and the Gateway.
- **Router** is deployed in the network to improve network coverage and connectivity.
- **Field Device** is attached to the process plant and collects data. It could be a sensor or an actuator.
- **Handheld** is a portable WirelessHART-enabled computer used to configure devices, run diagnostics, and perform calibrations.
- **Adapter** is a bridge device between the wireless mesh network and traditional wired HART devices.

B. *Existing Test Suites for Wireless Standards*

Although to the best of our knowledge, there is no existing test suite designed for WirelessHART standard, many testing and analyzing tools are available for evaluating the compliance of the DUTs with several existing wireless standards.

ZigBee aCT [18] is a ZigBee automated compliance testing solution that executes a sequence of Tx and Rx tests to characterize a DUT's compliance and performance in accordance with the IEEE 802.15.4 standard and generates detailed test reports. The main advantage of this solution includes test automation with minimal user input and the ability to save test results in easy-to-read report formats. ZigBee aCT performs several compliance tests on any or all of the 16 frequency channels numbered from 11 to 26. However, ZigBee aCT only focuses on a DUT's compliance in the MAC layer and lacks a thorough test of its network layer behavior. Also, there is no way for the users to inject any fault data thus it is difficult if not impossible to test its corresponding behaviors in the presence of ill-behaved stimuli.

Codenomicon Robustness Tester [19] for Bluetooth is a black-box testing product with ready-made Bluetooth test cases. The tests verify how well an implementation can withstand invalid and malformed traffic, thus resulting in improved product stability and security. The Codenomicon tester consists of a set of separate test suites, each of which tests a particular Bluetooth protocol layer or profile and all relevant protocols and profiles of Bluetooth are covered. The tests have been designed in accordance with Bluetooth Core specification 2.0 where applicable, but implementations based on any earlier versions of the specification may still be tested as well.

To ensure industry wide ubiquitous Wi-Fi, the Wi-Fi Alliance [20] proposes a certification program which includes a series of standardized interoperability tests. The Alliance has two approved standard test methodologies for Wi-Fi Certification: the original Wi-Fi certification methodology designed for PCs and Access Points and the new Wi-Fi Alliance test engine methodology which is targeted at application specific devices with embedded Wi-Fi connectivity. Among various test suites developed for Wi-Fi certification, the AzCert Wi-Fi certification test suite [21] is a semi-automated solution used by Wi-Fi Alliance authorized test laboratories. This solution enables users to reduce the learning curve and ongoing resources required for certification testing; reduce time spent on executing the Wi-Fi Alliance test plan; generate customized test stimuli using the Wi-Fi Traffic Generator (WTG); debug by running full test or specific test steps, and interpret information using detailed test results reporting.

C. *HTest for Wired HART Communication Protocols*

The HART Communication Foundation (HCF) is an independent, not-for-profit organization owning and managing all elements of HART technology. HCF tests the compliance of wired HART products using HTest which is a general purpose HART master software for PC with HART modem. HTest uses CINT [22], a simple interpreted script language to build, send, receive and display HART messages. By evaluating the correctness of the response data, the compliance of the DUT can be verified. With the release of WirelessHART standard and rapid emergence of WirelessHART devices in the market, it is necessary for the HCF to extend HTest to support wireless commands testing and assure the compliance of WirelessHART devices. The following of this paper will elaborate our effort of designing and implementing Wi-HTest to achieve this goal.

III. WirelessHART test specification and test scripts

A. Test Specification Overview

In developing a WirelessHART compatible field device, a variety of informal ad-hoc testing and formal tests are to be performed. HCF simplifies this test effort by supplying a test specification [23] for developers. All tests must be completed along with the test report prior to product release and product registration with HCF. The test specification provides clear test requirements and reduces the number of test plans that must be developed by the manufacturer. They can be used early in the development effort to informally verify functionality during implementation and are a useful part of a regression testing program as the field device is maintained and enhanced. Further, the test specification clarifies ambiguities in the protocol and is the final, definitive authority when interpreting the protocol.

This test specification uses a quasi "black box" approach to confirming compliance with WirelessHART standard. The complete set of tests consists of the following five phases and each phase contains multiple test descriptions that are intended for sequential execution.

- Boot-strap tests
- Single correspondent tests
- Multiple correspondent tests
- Multi-channel-selection tests
- Stress tests

The Boot-strap tests try to perform an audit of the command set implemented in the DUT through either maintenance port or wireless connection. They also set the DUT in an initialized state and test its join process into a specific WirelessHART network.

Based on the successful completion of all Boot-Strap tests, the single correspondent tests focus on a single logical RF channel and the DUT interacts directly with a Network Manager and Gateway. This series of tests examine that a wireless field device properly requests admission to the wireless network; accepts commands that condition its operation in the wireless network, including commands with a deferred execution; and operates synchronously with the peer device.

Different from the single correspondent tests, multiple correspondent tests verify that a wireless device properly interacts with multiple peers, including inferring information about those peers from received messages.

Multi-channel-selection tests extend the multiple correspondent tests by ensuring that a wireless device properly selects among multiple potential channels on which its schedule permits operation.

Finally, the stress tests combine all the prior tests into a single random sequence that serves to examine continuous device operations in a simulated field environment. The primary purpose of this phase is to confirm that the device will reliably interoperate with one another in a real-world environment.

B. WirelessHART Test Script

According to the WirelessHART test specification, we have written the test scripts for various test cases in each test phase. HCF also provides a script development manual [24] for the ease of the developers. Test scripts are small, narrowly-focused test applications. They are taken as input to feed in the Wi-HTest for establishing the test environments, generating proper test packets and conducting the compliance tests. Typically a test script includes two parts: The test configuration and the test body. The test configuration section initializes the Network Manager and Gateway, configures the Wi-Analys and sets up the RF Interface and various test parameters. Necessary virtual devices and corresponding communication schedules are also added to support network layer compliance tests. The test body is consisted of a sequence of small test steps. Each test step generates or manipulates a WirelessHART data packet by calling related libraries implemented in Wi-HTest. The test body then waits for the response from the DUT and verifies its compliance. The test script is written in C++ and the pseudo code of the test script for device join is presented in the Appendix. Readers are referred to the test specification for other concrete examples.

IV. Wi-HTest architecture

A. Overview

Wi-HTest extends HTest by supporting wireless commands to test WirelessHART-enabled devices. Figure 3 shows the actual hardware in the Wi-HTest test suite and the software architecture is depicted in Figure 4. Wi-HTest consists of two components: the Wi-HTest Host and a RF Interface. The Wi-HTest Host is responsible for overall control and execution of the input test scripts. It first configure the DUT with necessary information including the network ID, and the join key through the FSK modem. After that, according to the specific requirements of the scripts, the Wi-HTest Host generates either correct packets or manipulates the packets by injecting fault data into either the command payload or the headers of different layers. Wi-HTest Host then sends these packets to the RF Interface for transmission through the 802.15.4 radio. The RF Interface is a compact WirelessHART stack. It is responsible for low-level, time-critical communications to and from the DUT using its onboard wireless transceiver. Responses from DUT are forwarded back to the Wi-HTest Host and are also captured by Wi-Analys for post processing. Finally, the post process suite reads in the log recorded by Wi-Analys (especially the timing information of the response packets) and generates the corresponding compliance report for the DUT. The details of the system design of Wi-HTest are discussed in the following sections.

B. Wi-HTest Host Architecture

The Wi-HTest Host is implemented on a Linux system (shown on the left in Figure 3) and consists of three major modules: the RF Interface driver, network layer library, and the Wi-HTest engine. The architecture of the Wi-HTest Host is depicted in Figure 5. These modules coordinate closely

Fig. 3. An overview of Wi-HTest system

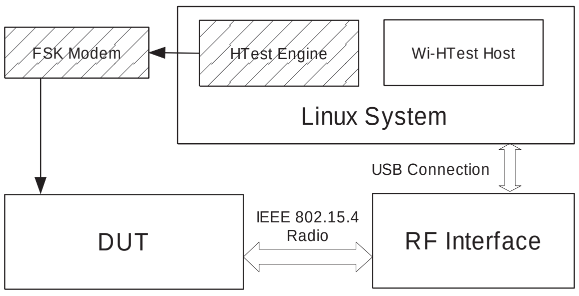


Fig. 4. The high level architecture of Wi-HTest

to achieve the following functionalities: 1) Read the test scripts as input and set up corresponding equipments and test environments; 2) According to the requirements of the test script, generate corresponding command payload and assemble it with proper network layer header. If necessary, inject designated errors into the network packet and further inform the data link layer and physical layer in which fields and how their headers should be manipulated. 3) Transmit the control information and data packets to the MAC layer for transmission and wait for the response from the DUT. Next we shall describe the details of each module.

*1) **RF Interface driver**:* The driver between the Wi-HTest Host and the RF Interface uses a simple private protocol for communication through USB. The protocol provides basic framing functions, such as preambles, delimiter, frame control and CRC error detection. The frame format of the protocol is shown in Table I.

There are three types of commands carried over the USB cable: commands from the Host[2] to configure the RF Interface (Type I), commands to relay data packets between the Wi-HTest Host and the DUT (Type II), and commands from the RF Interface to the Wi-HTest Host to update certain data structure in the Host (Type III).

Type I: Basically, Type I commands are mostly WirelessHART commands and are used to configure the RF Interface. However, these commands are further extended to

Byte	Format	Description
0-4	Unsigned-8	Preamble (0xFF)
5	Unsigned-8	Delimiter (0x86)
6	Unsigned-8	Frame length (exclude itself)
7	Bits-8	Frame Control
7.6-7.7	Enum-2	Normal Data (0) Acknowledge(3)
7.0-7.5	Bits-6	Frame counter
8-9	Unsigned-16	Command Number
10-n	Unsigned	Command Data
(n+1)-(n+2)	Unsigned-16	CCITT CRC-16

TABLE I

Frame format of the protocol between Host and the RF Interface

support the virtual device. For example, Command 967 is used by the Host to add a link assignment to the RF interface and Command 64521 further supports to add any link among the RF Interface, the virtual devices and the DUT. We will present the details of the virtual device in Section IV-B.2.

Type II: There is only one Type II command, Command 64513 defined to denote the data request from the network layer to the data link layer[3] or the data indication from the data link layer to the network layer. The data request message from the network layer to the data link layer contains a special header and the network layer payload. This header includes a bitstring indicating if and which MAC or physical header field should be manipulated to transmit false messages. The details of the packet manipulation in Wi-HTest will be discussed in Section IV-B.2.

Type III: Currently there is only one Type III command, command 64518, used by the RF Interface to update its ASN (Absolute Slot Number) to the Wi-HTest Host. This provides Wi-HTest Host a rough ASN snippet to fill in the network layer header. More Type III commands are to be introduced to provide the data sharing between the Host and the RF Interface.

The frame counter field guarantees the reliable communication between the Wi-HTest Host and RF Interface. Each end of the communication keeps two frame counters, one for itself and one for the other end. Each time it sends a frame, its own frame counter is incremented by one. When it receives a frame, the counter in the incoming frame is compared to the frame counter for the sender. If they are equal, the frame is expected. Otherwise, the frame is discarded silently. Whenever a correct frame is received, the receiver increments the frame counter for the sender by one.

*2) **The network layer library in Wi-HTest Host**:* The network layer is constructed as a library along with an independent receiving thread in Wi-HTest Host. The network layer library provides function calls to construct or manipulate the data payload and packet header while the receiving thread handles the response packet back from the MAC layer or processes received unsolicited messages.

We separate the network layer from the RF interface and

[2]In the following of the paper, we use "Host" and "Wi-HTest Host" interchangeably.

[3]In the following of the paper, we use "data link layer" and "MAC layer" interchangeably.

put it on the Wi-HTest Host for three practical reasons. First, compared with the MAC layer, most of the operations on network layer are not time critical. Given the limited memory and MCU resources, and stringent timing requirements on the RF Interface, putting the network layer on the Wi-HTest Host can save more resources for implementing Wi-HTest-specific modules on the RF Interface; Second, with the network layer on the Wi-HTest Host, it is more direct and convenient for the test scripts to inject fault data into the WirelessHART command payload, the network layer header, and even the MAC layer header. Otherwise, the test script has to convey these control information to the RF through various interface messages; At last, putting the network layer on the Host provides us the possibility and flexibility to simulate virtual devices and form a virtual network for multiple correspondent tests.

The network layer library provides plenty of useful function calls for supporting various network operations. For example, based on given parameters, a set of functions are used to construct network header while another function set is for parsing existing network layer packets. The library also contains functions for network layer initialization and configuration, building interface messages, enciphering, deciphering and authenticating network layer packets, and maintaining various communication tables in the network layer.

In each test case, when a transmit command is read in from the test script, the test engine in Wi-HTest Host formats either correct or manipulated network layer packets by calling related functions from the network layer library and forwards them to the RF driver for transmission; the independent receiving thread continuously monitors the incoming queue and handles different types of packets by calling corresponding callback functions in the incoming message processor. If the message is a response that the test engine is waiting for, it is stored in a shared buffer and the test engine is woken up for processing. For other cases, the message will be either discarded or be used to update relevant data structures. An example of such messages is the neighbor health report which is generated periodically by each device to update its status to its neighbors.

Packet Manipulation: To provide the tester complete control over the transmitted packet, a critical feature provided by the network layer library is the bitwise packet manipulation. It allows the testers to change any field of the network packets including the header and the command payload. Furthermore, the interface between the network layer and the RF Interface (Command 64513 in Section IV-B.1) enables us to specify which fields of the MAC layer and physical layer header will be manipulated using a bitstring and corresponding data fields. The first bit in the bitstring indicates if it is MAC (0) or physical layer (1) manipulation. For MAC layer the subsequent bits are the first byte, address specifier, sequence number, network ID, destination address, source address, PDU specifier, MIC, message length and applying superframe routing. For physical layer the subsequent bits are transmission offset and fixed timeslot. Bit value of 0 means no manipulation while 1 means

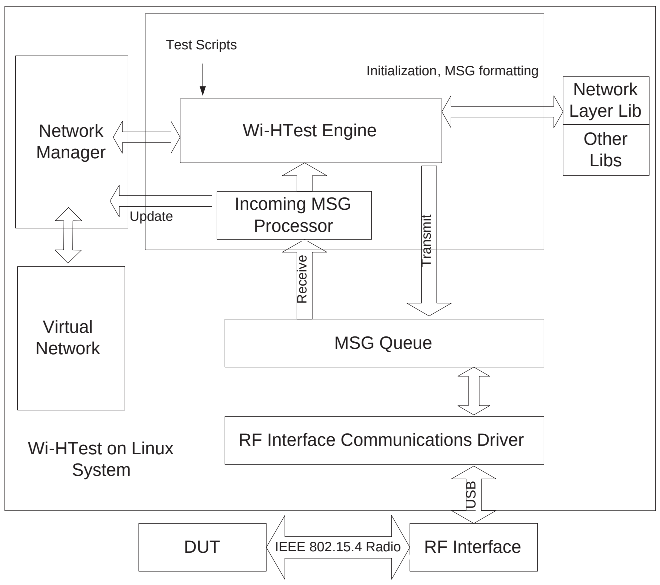


Fig. 5. The architecture of Wi-HTest Host

manipulated value should be used. The manipulation functions in the network layer library and the interface between the Wi-HTest Host and the RF Board provide the testers complete control over the packets (including the request, response and acknowledgement messages), and help them design arbitrary test cases for WirelessHART compliance evaluation.

Virtual Network: The traditional way to set up a testbed for network layer tests is to deploy exactly the same number of physical devices as needed in the experiment, and to configure each device according to the experiment configuration. This approach introduces the following difficulties for a wireless mesh testbed:

- Since the nodes communicate through wireless, we have to make sure that the nodes in the testbed are communicating among themselves correctly and reliably.
- The testbed can contain hundreds of nodes and it would be difficult just to set it up before putting the DUT in.
- It is a challenge to tell a physical node to misbehave in a controlled manner to simulate the interference.
- The approach does not scale. For different test cases, the physical devices have to be configured and organized differently. It will be costly to maintain different testbeds during different stages of a mesh network development or deployment.

Different from the conventional approach, in Wi-HTest, to support multiple correspondent tests which focus on evaluating DUT's network layer operations, we introduce two important concepts: virtual device and virtual network. Our goal is to achieve scalability by reducing the number of physical devices in the testbed as much as possible, and this is achieved by using the same antenna for multiple purposes. As WirelessHART is a TDMA-based protocol and provides network-wide time synchronization, each packet transmission or reception is

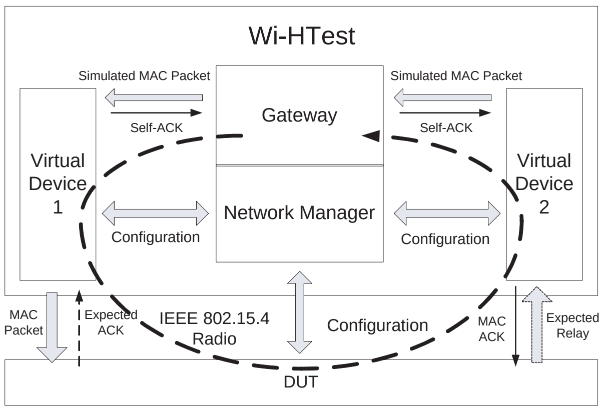


Fig. 6. An example of source routing among Gateway, two virtual devices and the DUT

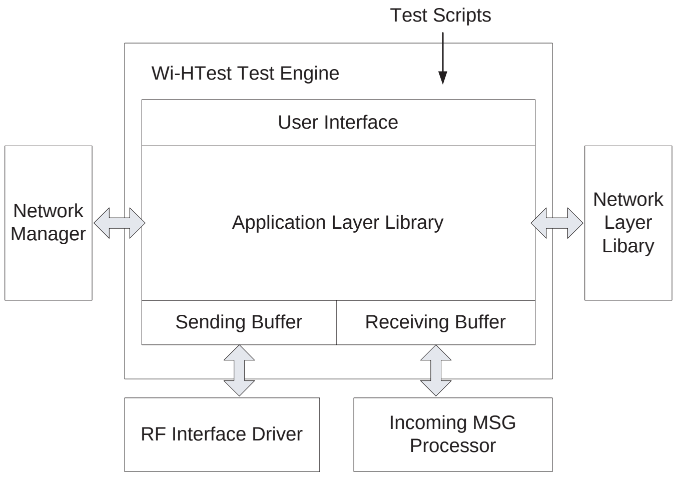


Fig. 7. The architecture of the Wi-HTest test engine

conducted in a dedicated timeslot with a fixed time offset. We take advantage of this accurate timing information in our virtual network approach: whenever a physical device tries to communication with the DUT on channel c at timeslot t, we choose the antenna that represents the same channel and perform the same communication at timeslot t. In this way, a set of virtual devices can replace the physical devices and form a virtual network for the DUT by carefully configuring their routing information and communication schedules. This makes the DUT believe that it is operating in a real WirelessHART network with multiple devices and then various network layer tests can be performed on the device.

Following the design of Wi-HTest, the virtual device also splits its network and MAC layer, and installs them on the Wi-HTest Host and the RF Interface respectively. Although physically all virtual devices' network layers reside on the same Wi-HTest Host, the Network Manager will allocate an independent session and corresponding table structures for each virtual device. Similar to the communication between the Gateway and the DUT, with the help of the network layer library, the tester will have complete control over the network layer communication between the Gateway and the virtual device. The tester can manipulate every field of the network header and payload to fulfil various testing purposes.

The MAC layer design of the virtual device is relatively more complex. To support virtual devices, the Network Manager will first configure the RF Interface through Type I command. It will allocate necessary superframes and links to satisfy the communication requirements. The configuration varies according to different test scenarios. In the multiple correspondent test phase, each test case has a pre-determined communication sequence among the Gateway, multiple virtual devices and the DUT. If the MAC communication is between the Gateway and the virtual device or between two virtual devices, the tester will first generate the packet with correct source and destination addresses in the MAC header. This packet will be transmitted on a dedicated link configured by the Network Manager and selected by the link scheduler. To completely conform to the WirelessHART standard, a self-ACK will be constructed or manipulated immediately in this case. The self-ACK will be transmitted on the same link with precise timing. On the other hand, if the communication is from Gateway/virtual device to the DUT, the testing packets will be generated in the normal way and the RF Interface will wait for the DUT's response. Once the response is back, it will be forwarded to the Wi-HTest Host for further processing.

Figure 6 illustrates a typical example of the communication among the Gateway, the DUT and two virtual devices (VD1 and VD2). The Gateway initializes an end-to-end communication to VD2 by constructing the network packet using the following source routing sequence: Gateway $\rightarrow$ VD1 $\rightarrow$ DUT $\rightarrow$ VD2. The test script first generates and transmits the MAC packet from the Gateway to VD1, the corresponding self-ACK will be automatically generated by the RF board. The test script will then go on constructing a normal MAC packet from VD1 to DUT with the same network payload. Under the fixed routing information, the DUT is expected to acknowledge this transmission in the same time slot and relay the network payload to VD2. After receiving the packet from the DUT, VD2 will forward it to the Wi-HTest Host and finish the compliance report. All these packets will be captured by Wi-Analys with their accurate timing information. In this way, a virtual WirelessHART mesh network is simulated.

*3) **Wi-HTest Test Engine**:* The heart of the Wi-HTest Host is a test engine, whose architecture is shown in Figure 7. The test engine is a C++ program executed in the CINT [22] environment. CINT is a C/C++ interpreter aimed at processing C/C++ scripts with reduced compile and link cycle. An important component of the test engine is the application layer library. Working together with the Network Manager and the network layer library, this library provides a bunch of supporting functions through the user interface to help testers generate various test scripts. These scripts implement the specific requirements of the test case by calling corresponding functions in the library. This working mechanism results in our rapid development of various test cases.

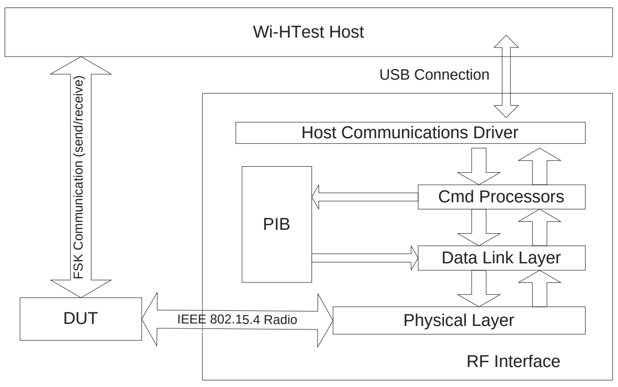


Fig. 8. The architecture of the RF Interface in Wi-HTest

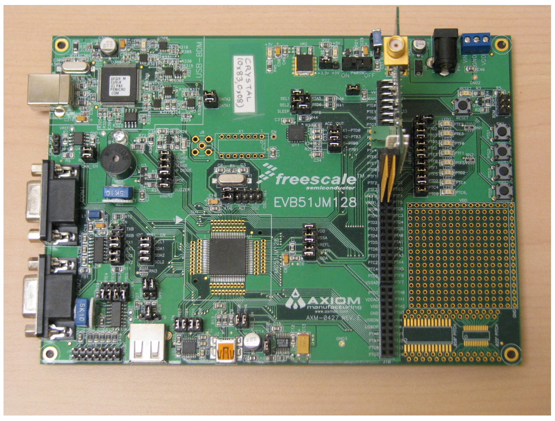


Fig. 9. Freescale JM128 Evaluation Board

The main functionality of the test engine is to read in the test scripts and generate corresponding wireless commands for the DUT. It then passes the commands through the network layer, assembles it with required header, and sends it to the RF Interface. The test engine then waits for the response from the DUT, puts it in the receiving buffer and verifies its correctness. On the other hand, the test engine will maintain timers for various timeout defined in the test script. If a timeout is triggered while no expected response is received from the DUT, the test engine will report corresponding error messages.

C. RF Interface Design

For the Wi-HTest Host to be able to talk to the DUT following the WirelessHART protocol, we connect the RF Interface through a USB cable to the Host. The RF Interface works as an Access Point between the Wi-HTest Host and the DUT. Figure 8 illustrates the overall architecture of the RF Interface.

*1) **Hardware Platform**:* We implement the RF Interface on the EVBJM128 [25] toolkit from Freescale which is shown in Figure 9. This toolkit has the following features and is powerful enough to meet the stringent timing requirements defined in the WirelessHART specification.

- Up to 50.33 MHz ColdFire [26] V1 core.
- Up to 128 KB of flash memory and up to 16K RAM with security circuit.
- Supports four low-power modes.
- On-board logic analyzer and virtual serial port.
- USB device mode and host mode support with Mini-AB USB connector.
- 8 user LEDs and 5 push buttons.

*2) **Real-time Embedded Compact Stack**:* The data link layer and physical layer on the RF Interface are collectively called the **Compact Stack** as the network layer is separated and put on the Wi-HTest Host. The compact stack is fully compliant with the WirelessHART specification, which means it must meet the stringent timing requirements defined in the specification. To address this strict time synchronization issue, as we discussed in [3], we proposed several solutions.

First of all, enciphering a frame and deciphering its acknowledgement (using AES-128 [27]) can take the stack out of synchronization. In order to speed up the enciphering/deciphering process, we take a streaming strategy. For example, if it is in a receiving slot, the stack starts to decipher the incoming frame when the first 16 bytes are received. In this way, the calculation intensive security checking can always be finished in time. Secondly, the interrupt handler is kept as simple as possible. Only those time critical jobs are put in the handler. Non-time-critical jobs are deferred and would be processed at appropriate time. Thirdly, we give the MAC layer the highest scheduling priority. Every time there is a frame to be processed, the MAC layer can preempt all the other tasks and get the MCU. There could be several jobs awaiting at any time in the MAC layer. We further prioritize these jobs to keep the stack in synchronization. For instance, transmitting a frame has priority over accepting a frame from the command processor.

For the limit of space, interested readers are referred to [3] for the details of the stack implementation.

*3) **The Command Processor**:* As the RF interface is basically a wireless Access Point for the Wi-HTest Host, all test commands are transmitted via it and all test responses are captured by the RF Interface. All commands and responses are handled in the command processor, and there can be four types of messages carried on the USB cable:

- *Board configuration commands:* These commands are issued by the Host to configure the RF Interface.
- *Test commands:* These commands are issued by the Host to be transmitted by the RF Interface to the DUT.
- *Test responses:* They are responses from the DUT to the Host.
- *Board updates:* They are updates from the RF Interface to the Host.

We use the simple communication protocol defined in Section IV-B.1 to differentiate the messages and provide error detection and retries. During initialization, the RF Interface waits for configuration commands from the Host. After it is set up properly, the RF Interface can accept test commands

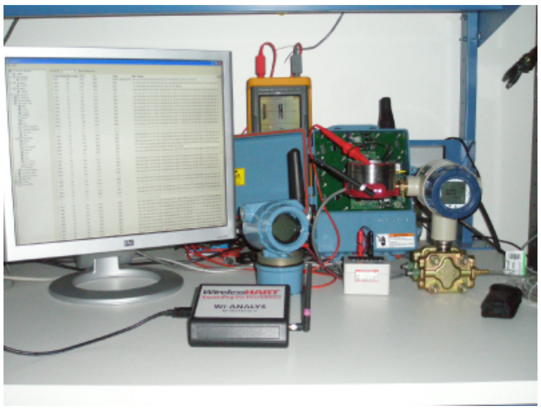


Fig. 10. Wi-Analys for capturing WirelessHART traffic

and receive responses from the DUT. If the commands are test commands, it encapsulates the command in a WirelessHART MAC frame and passes it to the data link layer, which would transmit the packet over the air to the DUT. In the other direction, every time the RF interface receives a response from the DUT (through the PHY and MAC layers), the RF Interface sends the response through the USB connection to the Wi-HTest Host.

V. Wi-Analys and Post Process Suite

Wi-HTest is a critical component in the compliance verification for WirelessHART-enabled devices, however it is not the only tool. Wi-HTest communicates with the DUT as if the DUT lives in a WirelessHART network. Wi-HTest itself could not collect all compliance information about the device. For example, Wi-HTest could verify the correctness of the device on the network, transportation, and application layers. But it could not tell if the device uses the correct message retry algorithm and whether the strict timing requirements defined in WirelessHART standard are met. A DUT conforms to the standard only if all its wireless transmissions over the air conform to the standard. For this reason, another two compliance verification components are also essential. They are the Wi-Analys and a post processing suite. Wi-HTest is the instigator that generates all the communication traffic in real-time. The HART Wi-Analys compliance verification receiver, Wi-Analys for short, captures and logs all the wireless traffic. The logs are post-processed by the post process suite to check if all the messages conform to the standard. The benefit of the log files is two folded. They serve as the raw data for ultimate compliance check; they also serve as the defense evidence when Wi-HTest is blamed for DUT's failure to pass the test.

A. *Wi-Analys*

Wi-Analys is designed to capture all 802.15.4 packets in the 2.4 GHz frequency range but focuses on those from WirelessHART devices. The receiver has the capability of capturing data on 16 WirelessHART channels simultaneously and at a speed of up to 1000 messages per second. As shown in Figure 10, Wi-Analys consists of a radio receiver box at the center front and a software suite running on a workstation. The receiver box is connected to the workstation via the USB cable. The software suite logs all captured WirelessHART messages on all channels. Wi-Analys also displays captured messages in an organized manner, either online or redisplaying a captured log file. The messages are interpreted and the fields in the messages, from physical layer fields all the way up to the application layer fields, could be displayed in columns. Further, intelligence is built-in to decipher the messages so that enciphered fields could be shown in plain text. Figure 11 demonstrates a screen capture of Wi-Analys display and readers can refer to [28] which has the same picture in higher resolution. The figure shows a partial segment of the DUT joining the network. We observe that in Figure 11 channel hopping is in effect and recorded in the channel column. We could also see that the application layer messages, i.e., HART commands and responses are displayed in plain text. As displayed in the left side of the figure, Wi-Analys has a built-in filter so that the user can narrow down the message list by specifying the parsing conditions on each field. Wi-Analys is a standalone product from HCF. It could be used as a real-time WirelessHART network monitoring tool.

B. *Post Process Suite*

The post process suite judges the successfulness of the compliance test. For each test case, a post process program reads the log file and analyzes it. Depending on the purpose of each test case, it will check the sequence of the messages the DUT transmitted, the transmission time points, the relationship of the messages, the content of the messages, etc. If all satisfy the standard, the test case is passed. Otherwise the place where the standard is violated will be reported.

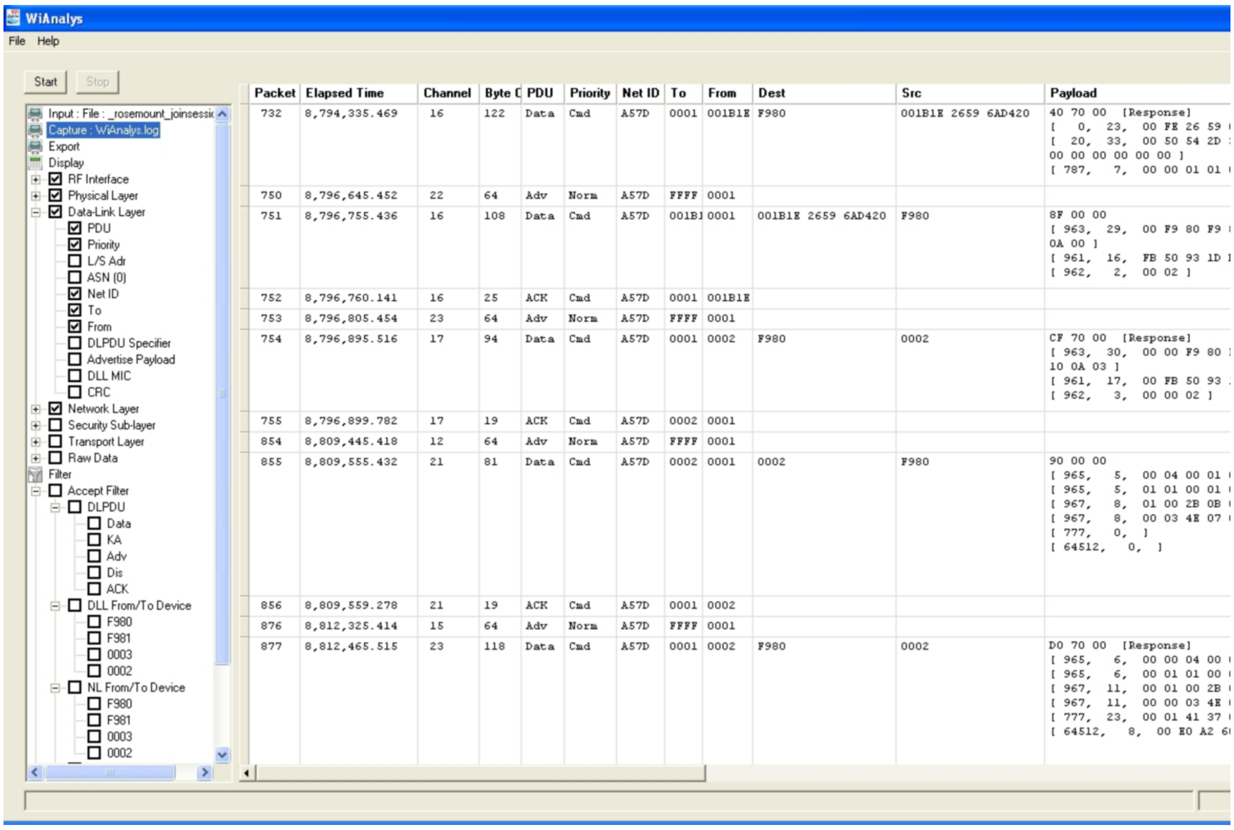
Wi-HTest, Wi-Analys and the post process suite constitute the complete compliance verification environment. In this environment, a device typically goes through the following steps to be certified by HCF. A complete test is composed of a set of test cases. Wi-HTest runs each test case with Wi-Analys capturing the messages through the whole test period. While Wi-HTest could declare if the device passes certain test cases. a post process program per case will analyze the corresponding log file to check if the device has strictly followed the standard during the test, especially satisfied the stringent timing requirements.

VI. Wi-HTest Test Cases

The WirelessHART compliance test is divided into many isolated test cases. They test the compliance of each protocol layer, from the physical layer up to the application layer. Wi-HTest runs each test case and generates the compliance report with the help from Wi-Analys and the post process suite. In this section, we present several representative test cases for demonstration. These test cases include the device join test, superframe management test, network routing test, burst data publishing test, and the network maintenance test.

A. *Device Join Test Case*

In this section we present an application layer test case example, i.e., device join test. Among many functions of a



- Input : File : _rosemount_joinsessi
- Capture : WiAnalys.log
- Export
- Display
  - ☑ RF Interface
  - ☑ Physical Layer
  - ☑ Data-Link Layer
    - ☑ PDU
    - ☑ Priority
    - ☐ L/S Adr
    - ☐ ASN (0)
    - ☑ Net ID
    - ☑ To
    - ☑ From
    - ☐ DLPDU Specifier
    - ☐ Advertise Payload
    - ☐ DLL MIC
    - ☐ CRC
  - ☑ Network Layer
  - ☐ Security Sub-layer
  - ☐ Transport Layer
  - ☐ Raw Data
- Filter
  - ☐ Accept Filter
    - ☐ DLPDU
      - ☐ Data
      - ☐ KA
      - ☐ Adv
      - ☐ Dis
      - ☐ ACK
    - ☐ DLL From/To Device
      - ☐ F980
      - ☐ F981
      - ☐ 0003
      - ☐ 0002
    - ☐ NL From/To Device
      - ☐ F980
      - ☐ F981
      - ☐ 0003
      - ☐ 0002

Packet	Elapsed Time	Channel	Byte C	PDU	Priority	Net ID	To	From	Dest	Src	Payload
732	8,794,335.469	16	122	Data	Cmd	A57D	0001	001B1E	F980	001B1E 2659 6AD420	40 70 00 [Response] [0, 23, 00 FE 26 59 [20, 33, 00 50 54 2D 00 00 00 00 00 00] [787, 7, 00 00 01 01
750	8,796,645.452	22	64	Adv	Norm	A57D	FFFF	0001			
751	8,796,755.436	16	108	Data	Cmd	A57D	001B1	0001	001B1E 2659 6AD420	F980	8F 00 00 [963, 29, 00 F9 80 F9 0A 00] [961, 16, FB 50 93 1D [962, 2, 00 02]
752	8,796,760.141	16	25	ACK	Cmd	A57D	0001	001B1E			
753	8,796,805.454	23	64	Adv	Norm	A57D	FFFF	0001			
754	8,796,895.516	17	94	Data	Cmd	A57D	0001	0002	F980	0002	CF 70 00 [Response] [963, 30, 00 00 F9 80 10 0A 03] [961, 17, 00 FB 50 93 [962, 3, 00 00 02]
755	8,796,899.782	17	19	ACK	Cmd	A57D	0002	0001			
854	8,809,445.418	12	64	Adv	Norm	A57D	FFFF	0001			
855	8,809,555.432	21	81	Data	Cmd	A57D	0002	0001	0002	F980	90 00 00 [965, 5, 00 04 00 01 [965, 5, 01 01 00 01 [967, 8, 01 00 2B 0B [967, 8, 00 03 4E 07 [777, 0,] [64512, 0,]
856	8,809,559.278	21	19	ACK	Cmd	A57D	0001	0002			
876	8,812,325.414	15	64	Adv	Norm	A57D	FFFF	0001			
877	8,812,465.515	23	118	Data	Cmd	A57D	0001	0002	F980	0002	D0 70 00 [Response] [965, 6, 00 00 04 00 [965, 6, 00 01 01 00 [967, 11, 00 01 00 2B [967, 11, 00 00 03 4E [777, 23, 00 01 41 37 [64512, 8, 00 E0 A2 6

Fig. 11. A segment of message sequence in the device join test case captured by Wi-Analys

WirelessHART network, device join is one of the most critical and difficult processes. Any DUT must first join the network before other tests could be performed on it. We will first describe the join process in the WirelessHART network and then demonstrate the complete test sequence in this test. The DUT's responses to each specific test step are captured by Wi-Analys and kept in the log. We will study the log carefully and focus on verifying the timing compliance of the response packet, the successful synchronization between the Wi-HTest and the DUT and the correct usage of various security keys during the device join process.

An overview of the join sequence of a WirelessHART device is shown in Figure 12. Wi-HTest plays the role of the Gateway and has partial functionalities of the Network Manager. The RF Interface works as the Access Point between the Gateway and the WirelessHART network. The general progression that must be followed for the joining device to become operational includes the following 6 steps:

- The device is configured with the network id and join key through a maintenance tool.
- The device listens for the network traffic to synchronize to the network clock and identify potential parents.
- The device then presents its credentials (including the device's identity and join key) to the Network Manager to demonstrate that the device is trustworthy.
- Once the Network Manager has scrutinized the device's credentials and deems the device trustworthy, it provides the first session key and network key to the device. The device is then in the quarantined state.
- The Network Manager then proceeds to integrate the device into the network by provisioning the device with normal superframes and links.
- Once the quarantined device obtains a session with the Gateway it becomes operational. It then begins acquiring the bandwidth and communication resources required to publish process data and events as dictated by its configuration.

Figure 11 demonstrates the message segment of a DUT joining the network. To make the figure more compact, we removed most of the advertisement messages from the Wi-Analys log. After reading in the test script for device join test, Wi-HTest first configures the RF Interface by writing superframes and corresponding links using command 965. After receiving the configuration information, the RF Interface starts to broadcast advertisements periodically twice per second. On the DUT side, upon powered up, it keeps listening for WirelessHART advertisement messages, one channel at a time. It keeps the information in the advisement messages from any device it could hear from. Once the DUT has heard from Wi-HTest and decides to join, it sends out the join request message, which is shown as message number 732 in Figure 11. The join request contains the device information

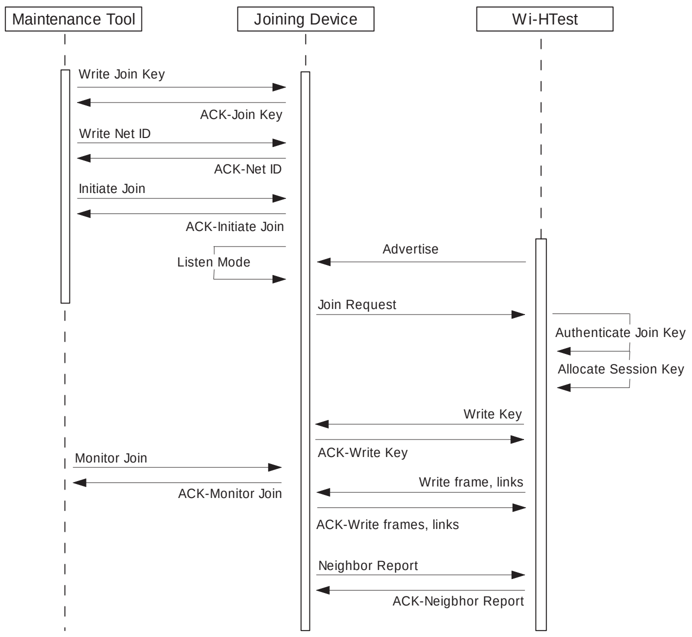


Fig. 12. The join sequence in WirelessHART standard

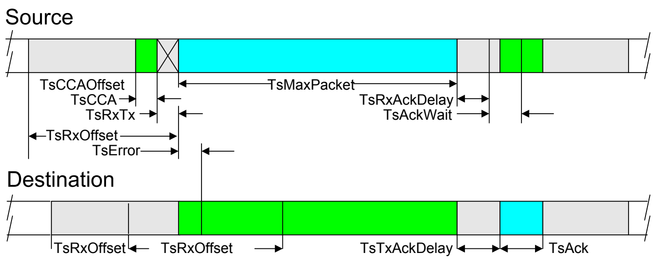


Fig. 13. The slot timing in WirelessHART standard

that is enciphered with the join key. In Figure 11, Wi-Analys deciphers the message and displays the device information in the network payload column. Wi-HTest uses the join key for decryption and verifies the correctness of the join request. It then sends out the join reply to the DUT, the message number 751. The join reply includes network information such as the network key, the assigned two-byte nickname and the session key. From then on, the Wi-HTest and the DUT will use the session key for network layer encryption instead of the join key. They will also use the network key for MAC layer enciphering. After successfully processing the join reply, the DUT sends back a confirmation message, number 754. Notice here in packet 754, we have the observation that the DUT is already using the assigned nickname while not the 8-byte long address for communication and the network layer payload can be deciphered successfully using the specific session key. Wi-HTest then sends out more information including the superframes and links to configure the DUT in message number 855, which is then confirmed by the DUT with message number 877. From this point on the DUT has joined the network and could communicate normally with Wi-HTest. This is a standard device join process and Algorithm 1 in the Appendix shows the detailed test script for this test case.

Figure 11 does show that the DUT constructs the join request and various response messages with correct command payloads and uses proper keys for network layer and MAC layer encryption and decryption. However, this is not sufficient to assert that the DUT has completely passed the device join compliance test. To claim that the DUT is fully compliant to the WirelessHART standard, the timing between the data request message and the corresponding ACK must be carefully measured. As we have shown in [3], Figure 13 depicts the specific timing requirement inside a WirelessHART time slot (10ms) and a receiver must acknowledge a packet within *TsTxAckDelay* time units after the end of the current message. This duration could vary within $\pm 100\mu s$ as is defined by the data link layer specification. By carefully evaluating the timestamps of the data request message and its corresponding ACK captured and recorded by Wi-Analys, we can see that their timing do not deviate more than $100\mu s$. This thus finally certificates the complete compliance of the DUT with the WirelessHART standard.

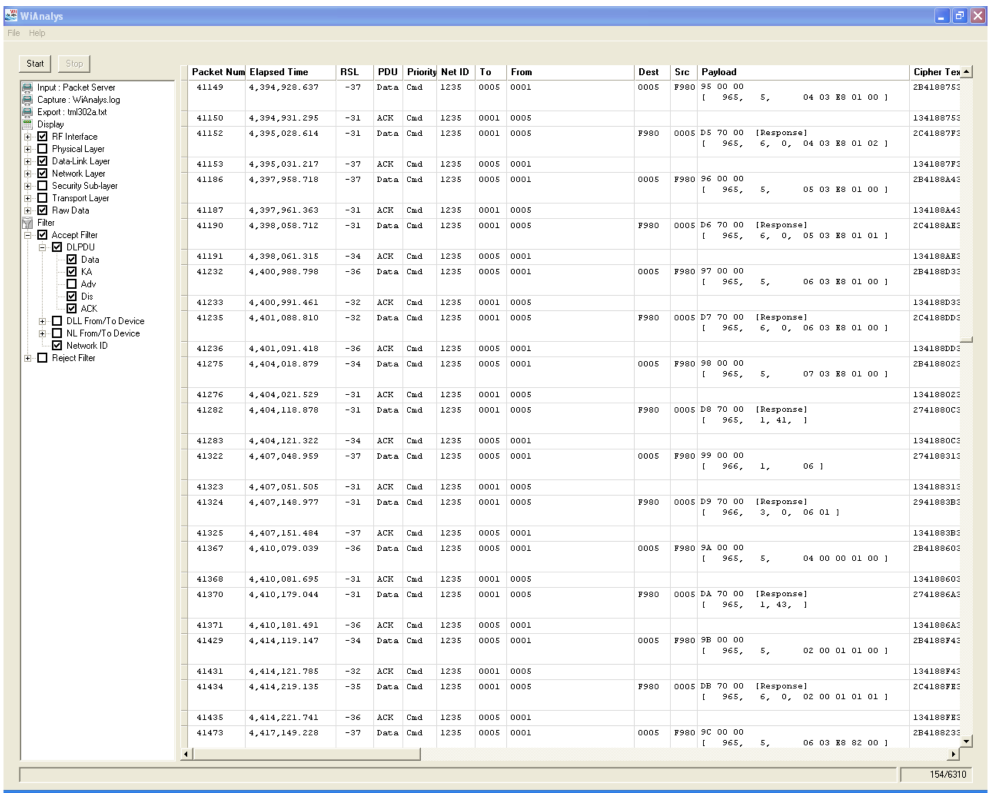
B. *Superframe Management Test Case*

After the DUT joins the WirelessHART network successfully, various single and multiple correspondent tests can be conducted on the DUT to thoroughly test its compliance to the WirelessHART standard. In this subsection, we will present the superframe management test which is a single correspondent test on MAC layer. We will describe the network routing test, burst data test, and network maintenance tests in the following sections. They are multiple correspondent tests focusing on verifying the DUT's network layer behaviors.

The superframe management test tries all ways to exercise the DUT's operations on superframe. It injects various possible errors into the command payload and evaluate the DUT's corresponding responses. The superframe management test consists of six separate test sequences as follows.

- Increase the number of superframes on DUT until its superframe table is full. After that, add one more superframe.
- Delete one superframe from the DUT and modify an existing one by providing invalid number of slots.
- Modify that superframe again with valid number of slots.
- Add a new superframe with an invalid mode.
- Delete two superframes from the DUT and then add another two, one with an ASN in the future and one with an ASN in the past.
- Delete all existing superframes on the DUT.

Figure 14 demonstrates a partial message segment of the superframe management test. Readers are referred to [29] for the complete test results captured by Wi-Analys. In Figure 14, the Gateway tries to add a new superframe to the DUT using command 965 in message number 41149. According to the command payload, the ID of this superframe is 04. It has 1000 slots (0x03E8) and is set active (0x01). The DUT confirms the success of this operation in message number 41152. It sets the command response code as 0 and returns the number of available slots in the superframe table which is 2. The test


WiAnalys

File Help

Start Stop

- Input : Packet Server
- Capture : WiAnalys.log
- Export : tml302a.txt
- Display
  - ☑ RF Interface
  - ☐ Physical Layer
  - ☑ Data-Link Layer
  - ☑ Network Layer
  - ☐ Security Sub-layer
  - ☐ Transport Layer
  - ☑ Raw Data
- Filter
  - ☑ Accept Filter
    - ☑ DLPDU
      - ☑ Data
      - ☑ KA
      - ☐ Adv
      - ☑ Dis
      - ☑ ACK
    - ☐ DLL From/To Device
    - ☐ NL From/To Device
    - ☑ Network ID
  - ☐ Reject Filter

Packet Num	Elapsed Time	RSL	PDU	Priority	Net ID	To	From	Dest	Src	Payload	Cipher Tex
41149	4,394,928.637	-37	Data	Cmd	1235	0005	0001	0005	F980	95 00 00 [965, 5, 04 03 E8 01 00]	2B4188753
41150	4,394,931.295	-31	ACK	Cmd	1235	0001	0005				134188753
41152	4,395,028.614	-31	Data	Cmd	1235	0001	0005	F980	0005	D5 70 00 [Response] [965, 6, 0, 04 03 E8 01 02]	2C41887F3
41153	4,395,031.217	-37	ACK	Cmd	1235	0005	0001				1341887F3
41186	4,397,958.718	-37	Data	Cmd	1235	0005	0001	0005	F980	96 00 00 [965, 5, 05 03 E8 01 00]	2B4188A43
41187	4,397,961.363	-31	ACK	Cmd	1235	0001	0005				134188A43
41190	4,398,058.712	-31	Data	Cmd	1235	0001	0005	F980	0005	D6 70 00 [Response] [965, 6, 0, 05 03 E8 01 01]	2C4188AE3
41191	4,398,061.315	-34	ACK	Cmd	1235	0005	0001				134188AE3
41232	4,400,988.798	-36	Data	Cmd	1235	0005	0001	0005	F980	97 00 00 [965, 5, 06 03 E8 01 00]	2B4188D33
41233	4,400,991.461	-32	ACK	Cmd	1235	0001	0005				134188D33
41235	4,401,088.810	-32	Data	Cmd	1235	0001	0005	F980	0005	D7 70 00 [Response] [965, 6, 0, 06 03 E8 01 00]	2C4188DD3
41236	4,401,091.418	-36	ACK	Cmd	1235	0005	0001				134188DD3
41275	4,404,018.879	-34	Data	Cmd	1235	0005	0001	0005	F980	98 00 00 [965, 5, 07 03 E8 01 00]	2B4188023
41276	4,404,021.529	-31	ACK	Cmd	1235	0001	0005				134188023
41282	4,404,118.878	-31	Data	Cmd	1235	0001	0005	F980	0005	D8 70 00 [Response] [965, 1, 41,]	2741880C3
41283	4,404,121.322	-34	ACK	Cmd	1235	0005	0001				1341880C3
41322	4,407,048.959	-37	Data	Cmd	1235	0005	0001	0005	F980	99 00 00 [966, 1, 06]	274188313
41323	4,407,051.505	-31	ACK	Cmd	1235	0001	0005				134188313
41324	4,407,148.977	-31	Data	Cmd	1235	0001	0005	F980	0005	D9 70 00 [Response] [966, 3, 0, 06 01]	2941883B3
41325	4,407,151.484	-37	ACK	Cmd	1235	0005	0001				1341883B3
41367	4,410,079.039	-36	Data	Cmd	1235	0005	0001	0005	F980	9A 00 00 [965, 5, 04 00 00 01 00]	2B4188603
41368	4,410,081.695	-31	ACK	Cmd	1235	0001	0005				134188603
41370	4,410,179.044	-31	Data	Cmd	1235	0001	0005	F980	0005	DA 70 00 [Response] [965, 1, 43,]	2741886A3
41371	4,410,181.491	-36	ACK	Cmd	1235	0005	0001				1341886A3
41429	4,414,119.147	-34	Data	Cmd	1235	0005	0001	0005	F980	9B 00 00 [965, 5, 02 00 01 01 00]	2B4188F43
41431	4,414,121.785	-32	ACK	Cmd	1235	0001	0005				134188F43
41434	4,414,219.135	-35	Data	Cmd	1235	0001	0005	F980	0005	DB 70 00 [Response] [965, 6, 0, 02 00 01 01 01]	2C4188FE3
41435	4,414,221.741	-36	ACK	Cmd	1235	0005	0001				134188FE3
41473	4,417,149.228	-37	Data	Cmd	1235	0005	0001	0005	F980	9C 00 00 [965, 5, 06 03 E8 82 00]	2B4188233

154/6310

Fig. 14. A segment of the message sequence in the superframe management test case

continues to add more superframes to DUT in message number 41186 and 41232. The return message number 41235 from the DUT shows that there is no more available slots for new superframe. The message number 41275 attempts to add one more superframe (ID = 07) and the DUT reports error status in message 41282 with response code 0x41 which means the superframe table in the DUT is full. After this test sequence, the test then deletes the superframe 06 in message number 41322 using command 966 and the DUT responses to it in message 41324 by showing that there is one slot available in the superframe table. In message number 41367, the test further tries to modify the existing superframe 04 by using invalid number of slots (0x00) and the DUT reports error status in message 41370 by presenting error code 0x43. In message number 41429, the test tries to modify the number of slots on superframe 02 from 1000 (0xE8) to 1 and the DUT confirms it by sending message number 41434 back including the updated information of superframe 02.

By injecting all possible configuration errors into the superframe table on the DUT, the superframe management test conducts thorough exercises on the DUT's superframe operations. The DUT passes this test only when all its responses match the requirements of the WirelessHART standard.

C. Graph Routing and Source Routing Test Case

This subsection describes the network routing test which focuses on verifying the DUT's network layer behaviors. There are two types of routing approaches adopted in WirelessHART standard: graph routing and source routing. WirelessHART supports graph routing for robustness. A graph is directional with only one sink node which is the destination of any message. In graph routing, a message is forwarded by the intermediate nodes to the next neighbor on the graph. Each node is pre-configured with a set of forwarding neighbors of a graph so that it can make the routing decision locally. The data source simply associates a graph with the message and sends it out. In this test case the DUT is configured with two graph neighbors, VD1 and VD2, to send message to the Network Manager and the Gateway. The device addresses used in this and following test cases in Section VI-D and Section VI-E are summarized in Table II.

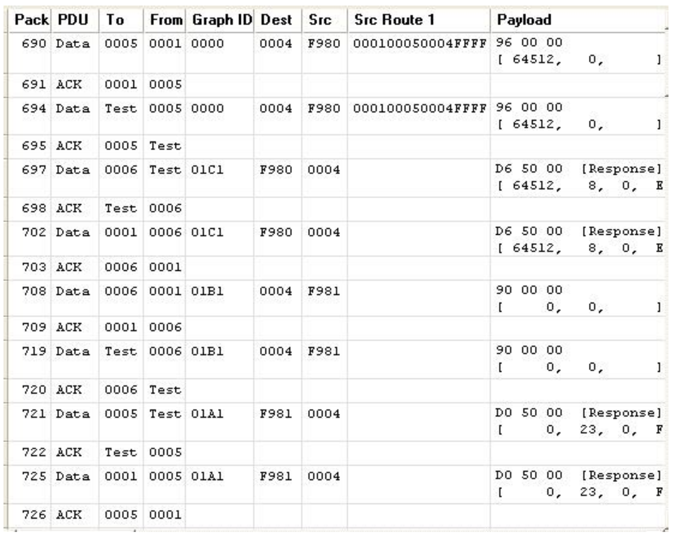
Device	**Address**	**Device**	**Address**
Network Manager	0xF980	DUT	0x0004
Gateway	0xF981	Virtual Device 1	0x0005
Access Point	0x0001	Virtual Device 2	0x0006

TABLE II
Device Addresses

In source routing the routing path is defined in the network header of the message. A routing device simply forwards the message to the next device in the path.

Fig. 15 shows the data request messages from the Network Manager and the Gateway to the DUT, and the corresponding response messages from the DUT.

- **Packet 690 to 695** The Network Manager sends Command 64512 to the DUT with source routing, whose list



Pack	PDU	To	From	Graph ID	Dest	Src	Src Route 1	Payload
690	Data	0005	0001	0000	0004	F980	000100050004FFFF	96 00 00 [64512, 0,]
691	ACK	0001	0005					
694	Data	Test	0005	0000	0004	F980	000100050004FFFF	96 00 00 [64512, 0,]
695	ACK	0005	Test					
697	Data	0006	Test	01C1	F980	0004		D6 50 00 [Response] [64512, 8, 0, E
698	ACK	Test	0006					
702	Data	0001	0006	01C1	F980	0004		D6 50 00 [Response] [64512, 8, 0, E
703	ACK	0006	0001					
708	Data	0006	0001	01B1	0004	F981		90 00 00 [0, 0,]
709	ACK	0001	0006					
719	Data	Test	0006	01B1	0004	F981		90 00 00 [0, 0,]
720	ACK	0006	Test					
721	Data	0005	Test	01A1	F981	0004		D0 50 00 [Response] [0, 23, 0, F
722	ACK	Test	0005					
725	Data	0001	0005	01A1	F981	0004		D0 50 00 [Response] [0, 23, 0, F
726	ACK	0005	0001					

Fig. 15. A segment of message sequence in the network routing test case

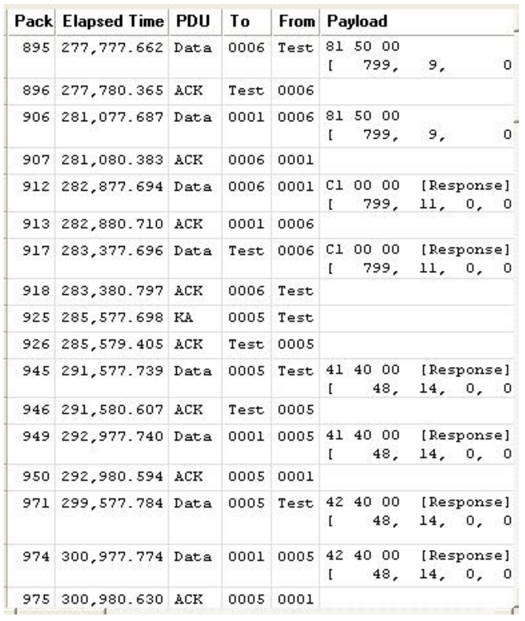
is AP, VD1, and DUT. The message is sent from the AP to the VD1 within the virtual network (Packet 690). The VD1 then forwards it to the DUT (Packet 697).

- **Packet 697 to 703** The DUT sends Command 64512 response back to the Network Manager using graph 0x01C1. The DUT selects the neighbor VD2 (Packet 697), who then forwards the message to the AP (Packet 702).
- **Packet 708 to 720** The Gateway sends Command 0 to the DUT using graph 0x01B1. The AP selects the neighbor VD2 (Packet 708), who then forwards to the DUT (Packet 719).
- **Packet 721 to 726** The DUT sends Command 0 response back to the Gateway using graph 0x01A1. The DUT selects the neighbor VD1 (Packet 721), who then forwards to the AP (Packet 725). Note this time the DUT selects a different neighbor from the previous response to Command 64512.

D. Burst Data Test Case

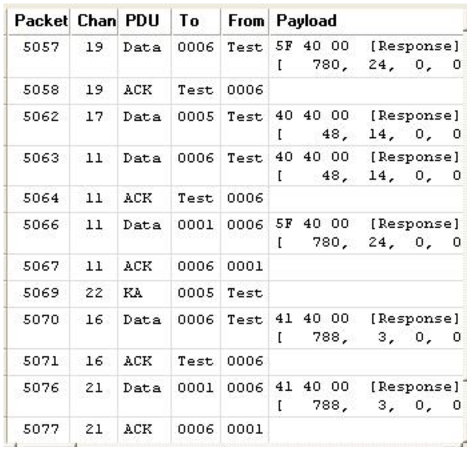
The main function of a sensor in a process plant is to periodically publish process value to the Host. In this test case the DUT is preconfigured to publish Command 48 every 8 seconds. After the session and links with the Gateway is configured, the DUT sends Command 799 to the Network Manager asking for the bandwidth to publish (Packet 895 in Fig. 16, forwarded in Packet 906). Since the Network Manager has already configured it, it simply replies with the route information in Packet 912 which is forwarded in Packet 917.

The DUT then sends out the first burst data in Packet 945, forwarded in Packet 949. About 8 seconds later (Refer to the second column *Elapsed Time* in Fig. 16) the next burst data is sent out in Packet 971, forwarded in Packet 974. This periodic data publishing will continue until the Gateway explicitly stops it by sending corresponding commands to the DUT.



Pack	Elapsed Time	PDU	To	From	Payload
895	277,777.662	Data	0006	Test	81 50 00 [799, 9, 0
896	277,780.365	ACK	Test	0006	
906	281,077.687	Data	0001	0006	81 50 00 [799, 9, 0
907	281,080.383	ACK	0006	0001	
912	282,877.694	Data	0006	0001	C1 00 00 [Response] [799, 11, 0, 0
913	282,880.710	ACK	0001	0006	
917	283,377.696	Data	Test	0006	C1 00 00 [Response] [799, 11, 0, 0
918	283,380.797	ACK	0006	Test	
925	285,577.698	KA	0005	Test	
926	285,579.405	ACK	Test	0005	
945	291,577.739	Data	0005	Test	41 40 00 [Response] [48, 14, 0, 0
946	291,580.607	ACK	Test	0005	
949	292,977.740	Data	0001	0005	41 40 00 [Response] [48, 14, 0, 0
950	292,980.594	ACK	0005	0001	
971	299,577.784	Data	0005	Test	42 40 00 [Response] [48, 14, 0, 0
974	300,977.774	Data	0001	0005	42 40 00 [Response] [48, 14, 0, 0
975	300,980.630	ACK	0005	0001	

Fig. 16. A segment of message sequence in the burst data test case



Packet	Chan	PDU	To	From	Payload
5057	19	Data	0006	Test	5F 40 00 [Response] [780, 24, 0, 0
5058	19	ACK	Test	0006	
5062	17	Data	0005	Test	40 40 00 [Response] [48, 14, 0, 0
5063	11	Data	0006	Test	40 40 00 [Response] [48, 14, 0, 0
5064	11	ACK	Test	0006	
5066	11	Data	0001	0006	5F 40 00 [Response] [780, 24, 0, 0
5067	11	ACK	0006	0001	
5069	22	KA	0005	Test	
5070	16	Data	0006	Test	41 40 00 [Response] [788, 3, 0, 0
5071	16	ACK	Test	0006	
5076	21	Data	0001	0006	41 40 00 [Response] [788, 3, 0, 0
5077	21	ACK	0006	0001	

Fig. 17. A segment of message sequence in the network maintenance test

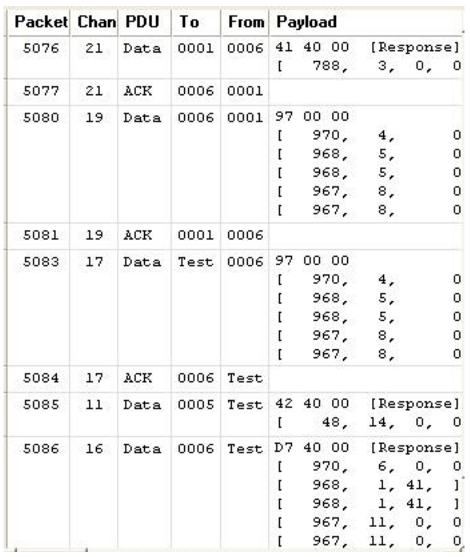
E. Network Maintenance Test Case

WirelessHART defines many ways to keep the mesh network healthy. For example, the device periodically sends health reports to the Network Manager; it also reports to the Network Manager if a neighbor is no longer communicating.

In this test case we shut down the VD1 after the DUT has begun publishing data. Fig. 17 shows that the DUT reported Command 788 (Path Down Alarm of the VD1) to the Network Manager (Packet 5070 forwarded in Packet 5077). Note that before the report the DUT sends message to the VD1 twice in packets 5062 and 5069, neither of them is acknowledged.

Fig. 17 also shows the reporting of Command 780 (Report Neighbor Health List) from the DUT in Packet 5057. It is interesting to see that the VD2 forwarded it (Packet 5066) after it has received a burst data from the DUT (Packet 5063).

Fig. 18 shows what happens after Command 788 is received. The Network Manager sends a message to the DUT (Packet



Packet	Chan	PDU	To	From	Payload
5076	21	Data	0001	0006	41 40 00 [Response] [788, 3, 0, 0
5077	21	ACK	0006	0001	
5080	19	Data	0006	0001	97 00 00 [970, 4, 0 [968, 5, 0 [968, 5, 0 [967, 8, 0 [967, 8, 0
5081	19	ACK	0001	0006	
5083	17	Data	Test	0006	97 00 00 [970, 4, 0 [968, 5, 0 [968, 5, 0 [967, 8, 0 [967, 8, 0
5084	17	ACK	0006	Test	
5085	11	Data	0005	Test	42 40 00 [Response] [48, 14, 0, 0
5086	16	Data	0006	Test	D7 40 00 [Response] [970, 6, 0, 0 [968, 1, 41,] [968, 1, 41,] [967, 11, 0, 0 [967, 11, 0, 0

Fig. 18. A segment of message sequence in the network reconfiguration

5080 forwarded in Packet 5083). The message contains: deleting the graph edge to the VD1 (Command 970), removing two links to the VD1 (Command 968), and adding two extra links to the VD2 (Command 967). The DUT responses it in Packet 5086 to notify the Network Manager that it is reconfigured successfully.

F. Discussion on the Virtual Network Approach

The advantage of the virtual network approach we introduced in Wi-HTest is that it provides a way to scale up the testbed setup and also offers very flexible functionality. In the test cases demonstrated in previous sections, the DUT cannot distinguish the difference between the test case from when it interacts with a real WirelessHART mesh network of multiple physical nodes, and the physical size of the Wi-HTest system is strikingly small. The height of the upright Access Point with the RF radio seen in Fig. 3 is just a little over 6 inches. With our approach, we can develop a comprehensive ZigBee testbed with the same amount of hardware as current Wi-HTest.

The next release for Wi-HTest will support 2 RF boards with one Host. Although there is only one DUT, for some tests, two antennae are needed. For example, in test case “TML401 Prioritization multiple simultaneous links”, the DUT will be configured with two transmission links at the same timeslot. Wi-HTest needs to listen on two different physical channels on that timeslot to find out if the DUT has selected the correct link for transmission. The synchronization of these RF boards adds complexity to Wi-HTest. We have devoted quite a bit of time just to get it right on the RF board. This vindicates in some sense our strategy to reduce the number of antennae in our approach.

While as many network nodes as possible can in principle be simulated, physically the number of radios required is no more than the maximum physical channels used by the mesh simultaneously at any given time. The testbed based on our approach is versatile in that any kind of tests can be conducted with the same hardware but different test scripts. Our hybrid approach of using radios to simulate environment interferences makes mesh network development and deployment not only more realistic but also more manageable. However, we should point out that we do not claim that our approach will work universally well for all application domains. In particular, the following limitations are challenges to extending our approach to other domains.

- **Location Awareness**. If message delay is used to locate network nodes, our approach is limited as we cannot fake different locations of the virtual devices. The limited simulation we can achieve is by changing the transmission powers to simulate different virtual device locations or mobile devices. However, for low power, low data rate, and small area mesh networks, using message delay for location awareness may be too hard to achieve.
- **Physical Channels**. Although one radio for one physical channel is reasonably sufficient for the process control domain, we cannot realistically simulate a real world environment in which multiple transmissions happen on one channel. For example, two radios sufficiently far apart may be able to use the same physical channel to communicate different messages. However, it is probably uncommon for the same physical channel to be used for different communications in a small-area wireless mesh network as is the case for industrial process automation, for which the distances between any two nodes controlling the same devices are relatively small.
- **Total Timing Fidelity**. Although it may be doable, it will be difficult to reproduce in real time the sequence of all the messages produced by a real mesh network.

VII. Lessons Learnt

In this section, we share some useful lessons we learnt during our design and development of Wi-HTest. We believe that these experience would be valuable for those who are interested in the inside of Wi-HTest or those who are going to design and implement similar compliance testing suites for other wireless standards.

- An important step in the design phrase is to estimate the hardware resources needed for specific development purpose. For example, the memory size and the MCU speed. Based on these resource requirements, the most proper hardware platform available should be selected. During our development, we had to switch from QE128 toolkit to JM128 board for larger memory size thus suffered incremental development and unexpected delay.
- Software architecture should be designed as flexible as possible. This makes the new features of the software be plugged in easily and seamlessly. In our initial design, Wi-HTest is a sequential processing and only supports single correspondent tests. To further support network and application layer tests, we had to revise the architecture of Wi-HTest to support virtual device/network and mul-

tiple DUTs. This revision introduced extra delay to our development.

- Timing is the most fundamental and critical part in Wi-HTest. All the communications in every layer are based on the accurate timing information. We spent a huge amount of time on achieving the accurate timing in the 10ms timeslot defined in the WirelessHART standards and the network-wide synchronization.
- For successful development, especially of the commercial products in embedded systems, codes with built-in debugging functions are necessary. Without the supporting debug functions, we have to play with the low-level codes every time and the memory usage in the system is difficult to be traced. This could make the debugging process inefficient and timing-consuming.

VIII. CONCLUSION

This paper presents the architecture of the Wi-HTest test suite, a critical part of the compliance verification tool for real-time WirelessHART network. We also describe Wi-Analys and the post process suite for capturing, analyzing the response from the DUT and finally generating the compliance test report. We describe the WirelessHART test specification and the structure of the test scripts. Several representative test cases on different communication layers are demonstrated to show that Wi-HTest, together with Wi-Analys and the post test suite provides an efficient test automation suite for WirelessHART compliance test. The compliance verification deals with both functional correctness as well as timing correctness. A critical measurement is that the MAC layer acknowledgement for a data request spanning a complex chain of events must not exceed a 10ms time slot. This has been incorporated into our test environment to guarantee the real-time communication of the WirelessHART network. We also describe and the virtual network approach that is applied in Wi-HTest to achieve scalable testbed setup especially for testing network layer behaviors, and discuss its advantages and limitations.

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APPENDIX

Alg 1 Test Script for Device Join Test

```
TEST CONFIGURATION

{Equipment Setup}
Tester with 1 RF Interface (RF1).
One DUT with Maintenance Port connected to Tester.
Log RF and wired communications.

{Initialize test}
CALL InitializeTest ()

{Initialize the network}
GENERATE NETWORK (NetID=1, cm=all 15 channels)
GENERATE SESSION NetID.NetKey

{Initialize the Network Manager}
GENERATE SESSION NMUnicast
GENERATE SESSION-LIST SList
SList.ADD(NMUnicast)

{Generate initial Superframes}
GENERATE SUPERFRAME JoinFrame (250ms-1s)
GENERATE SUPERFRAME CommFrame (500ms-2s)
GENERATE SUPERFRAME-LIST SFList
SFList.ADD (JoinFrame)
SFList.ADD (CommFrame)

{Generate a placeholder for DUT}
GENERATE DEVICE NicknameDUT
GENERATE SESSION JoinKey
SList.ADD(JoinKey)

{Generate an initial route and graph}
GENERATE ROUTE Route1
GENERATE GRAPH Graph1 (0x0100-0xFFFF)
GENERATE LINK FOR JoinFrame:
    LinkJF1 (DUT to Tester)
    LinkJF2 (Tester to DUT)
GENERATE LINK-LIST Links
Links.ADD(LinkJF1)
Links.ADD(LinkJF2)

{Configure the tester "RF1" with setup 1A}
CONFIGURE RF1 with JoinFrame, NetID, NetKey and Gateway Address

TEST BODY

{Find and reset the device}
CALL IdentifyDevice (TML102.A.001)
CALL ResetDevice (TML102.A.002)

{Provision the device with a NetID}
CALL ProvisionDevice(NetID, JoinKey, TML102.A.003)

{Set advertise to a occur at a random number of frames in time send force join}
GENERATE NUMBER NumFrames(1-4)
SET RF1.AdvertiseInterval = (CommFrame.NumberOfSlots * NumFrames)
SET ShedTime = RF1.AdvertiseInterval *15

SEND Cmd 771 ( "Join Now", ShedTime)
IF ResponseCode == 0
    VerifyResponseAndByteCount (0, 5+2, TML102.A.004a)
ELSE
    VerifyResponseAndByteCount (8, 5+2, TML102.A.004b)
    SET ShedTime = shed-time
END IF

IF (join-mode != "Join Now")
    Test Result is FAIL
IF (shed-time != ShedTime)
    Test Result is FAIL

{Monitor the progress}
SEND Cmd 769
CALL VerifyResponseAndByteCount (0, 14+2, TML102.A.007)
IF Wireless-Operation-Mode != "Active Search"
    Test Result is FAIL
ENABLE RF1

{Assimilate the device and analyze the Join Request}
CALL PollCmd769 (0x001F, 0xFFDF, ShedTime, 1, TML102.A.009.x)
SET NPDU = SessionKey, JoinKey, NMShortAddress, -1, -1,
    DUTUniqueID+HCF OUI, Graph1
ParseNetworkPDU (NPDU, TML102.020)
RECORD Join-Nonce for device NicknameDUT

IF Transport-Byte.Acknowledged bit set
    THEN Test Result is FAIL
IF Transport-Byte.Response bit is clear
    THEN Test Result is FAIL
IF Transport-Byte.Broadcast bit is set
    THEN Test Result is FAIL

{Parse Payload: must be a join request (Cmd 0 + Cmd 20 + Cmd 787 Responses.}
SET cmds[] to 0,20,787
ParseAppPDU(3, cmds , cmdPDU[ ], TML102.A.012)
IF cmdPDU[0].data != Cmd 0 data from IdentifyDevice()
    THEN Test Result is FAIL
IF cmdPDU[1].data != LONG-TAG
    THEN Test Result is FAIL
CALL ValidateCmd787Rsp( CmdPDU[2], GW-Nickname, TML102.A.015)

{Write DUT network key and nickname address and session with NM as the Join Response CREATE PAYLOAD "Join Response" with Cmd 961, 962, 963}
CREATE PAYLOAD "Join Response" with Cmd 961, 962, 963
SET Cmd961.Network-Key to NetKey
SET Cmd961.ASN to 0
SET Cmd962.Nickname to NicknameDUT

{Send a full length Cmd 963}
NMUnicast.BuildWriteSessionCmd (Cmd963, FALSE)

{Send these as a join response to the DUT (cmds 961, 962, 963)}
CREATE NLPDU from PAYLOAD using JoinKey and Join-Nonce
XMIT NLPDU

{Wait for reply}
SET Timeout = 5 * JoinFrame length
CALL PollCmd769 (0x009F, 0xFFDF, Timeout, 1, TML102.A.016.x)

{Next, analyze the received packet NLPDU (Join Request) Short NM Address, Short DUT address}
SET NPDU = SessionKey, JoinKey, NMShortAddress, -1, NicknameDUT, -1, Graph1
ParseNetworkPDU (NPDU, TML102.A.020)

IF Transport-Byte.Acknowledged bit set
THEN Test Result is FAIL
IF Transport-Byte.Response bit is clear
THEN Test Result is FAIL
IF Transport-Byte.Broadcast bit is set
THEN Test Result is FAIL

{Parse the Response: must be Cmd 961 + Cmd 962 + Cmd 963 Responses.}
SET cmds[] to 961, 962, 963
ParseAppPDU(3, cmds , cmdPDU[ ], TML102.A.018)

IF cmdPDU[0].Network-Key != NetKey
THEN Test Result is FAIL
IF cmdPDU[0].ASN != 0
THEN Test Result is FAIL
IF cmdPDU[1].Nickname != NicknameDUT
THEN Test Result is FAIL

NMUnicast.ParseWriteSessionRsp(cmdPDU[2], SList, FALSE, 0, TML102.A.022)

{Check device nickname address via maintenance port}
SEND Cmd 781
CALL VerifyResponseAndByteCount (0, 4, TML102.A.023)

IF Cmd781.Nickname != NicknameDUT
THEN Test Result is FAIL

END TEST CASE
```